

# Final report: Large-scale stratospheric transport processes (NAG 1-2027)

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## 1 Scientific issues

### (a) *The Brewer-Dobson circulation: tropical upwelling*

The paradigm of the “extratropical wave pump” cannot explain the observed pattern of tropical upwelling, because of the need for mean (residual) flow across the deep tropics. Such flow requires either that there is enough wave pumping within the tropics to support flow across angular momentum surfaces there, or (as in the tropospheric Hadley cell) that the flow—whether driven by extratropical wave pumping or by local thermal forcing—is nonlinear enough to expel angular momentum gradients from the tropics. In a 2D model of the response of the stratosphere to specified wave drag, we found that a reasonable meridional circulation resulted, provided the wave drag reached sufficiently close to the equator. In the upper stratosphere, the flow was found to be nonlinear; in the lower stratosphere, however, the response was linear and dependent on the weak but inevitable model viscosity. Adding thermal driving made the circulation more realistic, but thermal driving alone could not explain the distribution and magnitude of the observed upwelling. The dependence on unrealistic model viscosity is unsatisfactory, but may indicate the need for *in situ* wave stresses within the tropics to explain the observed behavior. This work is described in Plumb and Eluszkiewicz (1999).

### (b) *Mixing into the polar vortices*

The evolution of tracer-tracer relationships within the polar vortices during winter have been used to isolate non-transport effects such as ozone loss,

on the grounds that transport effects are eliminated by using a standard tracer (usually  $\text{N}_2\text{O}$  or  $\text{CH}_4$ ) as a coordinate. However, observations (*e.g.*, Michelson et al. [1998a,b; 1999]) also show evolution of relationships between tracers that have no known chemical loss processes. In fact, the (often implicit) assumption that transport cannot change these relationships is wrong: while *advection* cannot do so directly (since both mixing ratios are preserved under advection), *mixing* (which is usually consequent on advective stirring) will change the relationship wherever the tracer-tracer curve is nonlinear. Using both 2D and 3D model results we showed [Plumb et al., 2000] that the observed changes in conserved tracer-tracer relationships can be explained in this way, and that the observations imply that vortex air in the lower stratosphere is almost, but not quite, isolated from midlatitude air in late winter, prior to vortex breakdown.

(c) *The latitudinal structure of “age” in the stratosphere*

“Mean age” has proven useful as a diagnostic of stratospheric transport, and as a benchmark for assessing the simulation of transport processes in stratospheric models (*e.g.*, see the “Models and Measurements II” report). In a conceptual “leaky pipe” model of the stratosphere (and motivated by some model results) we investigated the meridional structure of mean age, particularly the gross tropics-to-midlatitude gradient [Neu and Plumb, 1999]. We found (in agreement with results from more complete models) that, in the realistic limit of negligible vertical (diabatic) diffusion, this gradient is independent of the rate of mixing across the subtropics and is, in fact, dependent only on the strength of the mean circulation. This result appears counterintuitive: at first sight, one might expect increased mixing to reduce the gradient. However, tropical air is the source of midlatitude air, and so, while increased mixing increases the age of tropical air, midlatitude age increases in consequence by the same amount, leaving the gradient unchanged.

(d) *The subtropical “tracer edges”*

It is now well known that tracer structures in the stratosphere exhibit a well marked “edge” in both winter and summer subtropics, at which strong gradients separate tropical from midlatitude mixing ratios. We have documented, from observations, the seasonal evolution of these edges throughout the stratosphere, and described the dynamics of their formation and evolution. In the analysis of observations, tracer probability density functions (PDFs) were constructed from the 7 months of CLAES  $\text{N}_2\text{O}$  data and from 6 years of HALOE  $\text{CH}_4$  data. The locations of the subtropical gradients were

determined from the location (*i.e.*, the latitudinal support) of the minima in the PDF. Results show the seasonal variation to be fairly straightforward. In early winter, the edge moves equatorward with the onset of westerlies, which appears to be a direct consequence of erosion by breaking Rossby waves in the surf zone. During mid-to-late winter, the edge remains almost static; in summer, it drifts poleward and becomes less sharp, but is maintained throughout the summer. Model studies have shown the location of the summer edge to be determined by diabatic effects. This work, which was done in collaboration with Dr Lynn Sparling at NASA/GSFC, formed the basis of Jessica Neu's Ph. D. thesis. A description of the observational work is submitted for publication [Neu et al., 2001], and a paper on the modeling work will be submitted in the near future.

*(e) Transport in the lower troposphere*

In the extratropical tropospheric interior, material is transported quasi-horizontally by synoptic scale eddies, although moist processes (including convection) introduce complexities beyond simple mixing along (dry) isentropic surfaces. Near the surface, however, a distinct mode of transport occurs. As a fundamental part of the baroclinic instability process, cold air surges equatorward near the surface (in synoptic structures known as "cold air outbreaks"), undercutting overlying warm air. Near-surface diabatic processes inevitably act to warm this cold air, thus permitting cross-isentropic, equatorward flow. The dynamics of this process, discussed by Held and Schneider [1999], ensure that this flow is contained within the "surface layer", comprised of isentropic surfaces that somewhere intersect the surface. This may be the most important mode of diabatic transport in the extratropical troposphere. We have run several simulations of tracer transport in an idealized GCM (see Fig. ??, below). We are currently analyzing these experiments, using a novel coordinate system we have devised to deal with the otherwise tricky surface layer. This work, which was supported in part by this grant, comprises Tieh Yong Koh's Ph. D. thesis; a paper describing the main body of the work will be submitted for publication in the near future.

*(f) Tracer modeling during SOLVE*

Prior to and during the SOLVE campaign, we ran tracer experiments with the three-dimensional "MATCH" CTM, driven with the NASA DAO assimilated winds and temperatures. Winds and temperatures for the period 980901-990831 were recycled for 10 years to set up a climatological

state appropriate for 990901; subsequently, the model was run through the SOLVE winter (through 000331) using contemporaneous winds and temperatures. Tracers run were  $\text{CO}_2$  (using an historical time series for surface  $\text{CO}_2$  extrapolated after mid-1999); CFC-11,  $\text{NO}_y$ ,  $\text{N}_2\text{O}$ , and age. Sources and sink rates for CFC-11,  $\text{N}_2\text{O}$  and  $\text{NO}_y$  were specified from output from a two-dimensional model (no sedimentation of  $\text{NO}_y$  was included). For the most part, tracer structures on isentropic surfaces were qualitatively consistent with those observed. However, the dynamic range of tracer mixing ratios at ER2 altitudes in early winter was much less than observed: within the vortex, the model has (marginally) inadequate descent of tracer isopleths at this time. However, later in the winter agreement between model and observations is very good. We have analyzed many aspects of the model results during this period, focusing on the diabatic and tracer isopleth descent, and on mixing between vortex and midlatitude air. This work is described in Plumb et al. [2001].

*(g) 3D modeling of "mean age"*

Using the 3D CTM described above, we have run several experiments simulating mean age in the stratosphere and mesosphere, in order to investigate the sensitivity of the simulation to model characteristics. The simulation of age has been shown to be a valid and useful test of a model's simulation of stratospheric tracer transport. We have run the CTM driven by assimilated winds, and by winds from a GCM, with both semi-Lagrangian and the newer "spitfire" advection scheme. While some differences were found, all simulations were similar; in particular, they all understate mean age by about 2 years in high altitudes and latitudes, relative to values determined from observations of  $\text{CO}_2$  and  $\text{SF}_6$ . The discrepancies between model and observation are evident in the tropics and permeate the entire region. The problem could be excessive tropical upwelling, or excessive vertical diffusion. In a collaborative project with Dr Natalie Mahowald (UC Santa Barbara), funded from other sources, we are developing an isentropic coordinate version of this CTM. It is hoped that this version of the model will reduce artificial vertical (diabatic) diffusion arising from the grid structure.

*(i) Models and Measurements II*

The PI participated as an organizer of the "Models and Measurements II" exercise, taking a lead role in the planning of transport experiments. He also participated as a member of the working group led by Dr Tim Hall, which analyzed the transport experiments. Results of this exercise were included

in the Models and Measurements II report [Park et al., 1999] and in Hall et al. [1999].

## 2 Education

Two graduate students (T.-Y. Koh and J. L. Neu) supported by the project completed their Ph. D. during this period.

## 3 Publications supported

### *Theses:*

Koh, T.-Y.: Transport by baroclinic waves in the lower troposphere. *Ph. D. Thesis*, M. I. T., 2000.

Neu, J. L.: Tropical transport and the seasonal variability of the subtropical “edges” in the stratosphere. *Ph. D. Thesis*, M. I. T., 2000.

### *Published:*

Hall, T.M., D.W. Waugh, K.A. Boering, and R.A. Plumb: Evaluation of transport in stratospheric models. *J. Geophys. Res.*, **104**, 18815-18839 (1999).

Neu, J.L., and R.A. Plumb: Age of air in a “leaky pipe” model of stratospheric transport. *J. Geophys. Res.*, **104**, 19,243-19,255 (1999).

Plumb, R.A., and J. Eluszkiewicz: The Brewer-Dobson circulation: dynamics of the tropical upwelling. *J. Atmos. Sci.*, **56**, 868-890 (1999).

Plumb, R.A., D.W. Waugh, and M.P. Chipperfield: The effects of mixing on tracer relationships in the polar vortices. *J. Geophys. Res.*, **105**, 10,047-10,062 (2000).

Sobel, A.H., and R.A. Plumb: Quantitative diagnostics of mixing in a shallow-water model of the stratosphere. *J. Atmos. Sci.*, **56**, 2811-2829 (1999).

*Submitted* (these can be obtained at <http://www-caps.mit.edu/~rap>):  
Neu, J. L., R. A. Plumb, and I. Sparling: The subtropical tracer edges in the stratosphere and their seasonal variation. Submitted to *J. Geophys. Res.*, 2001.

Plumb, R.A., W. Heres, J. L. Neu, N. Mahowald, J. del Corral, G. C. Toon, E. Ray, F. Moore, and A. E. Andrews: Global tracer modeling during SOLVE:

high latitude descent and mixing. Submitted to *J. Geophys. Res.* (SOLVE Special Issue), 2001.

Plumb, R. A.: Stratospheric transport. Submitted to *J. Met. Soc. Japan* (Hirota Retirement Special Issue), 2001.

Mahowald, N. M., R. A. Plumb, P. J. Rasch, J. del Corral, F. Sassi, and W. Heres: Stratospheric transport in a 3-dimensional isentropic coordinate model. Submitted to *J. Geophys. Res.*, 2001.